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# Evaluation of Human Exposure to Ambient PM<sub>10</sub> in the Metropolitan Area of Mexico City Using a GIS-Based Methodology

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## ABSTRACT

The main goal of this study was to evaluate the magnitude of outdoor exposure to fine particulate matter (PM<sub>10</sub>) potentially experienced by the population of metropolitan Mexico City. With the use of a geographic information system (GIS), spatially resolved PM<sub>10</sub> distributions were generated and linked to the local population. The PM<sub>10</sub> concentration exceeded the 24-hr air quality standard of 150 µg/m<sup>3</sup> on 16% of the days, and the annual air quality standard of 50 µg/m<sup>3</sup> was exceeded by almost twice its value in some places. The basic methodology described

in this paper integrates spatial demographic and air quality databases, allowing the evaluation of various air pollution reduction scenarios. Achieving the annual air quality standard would represent a reduction in the annual arithmetic average concentration of 14 µg/m<sup>3</sup> for the typical inhabitant. Human exposure to particulate matter (PM) has been associated with mortality and morbidity in Mexico City; reducing the concentration levels of this pollutant would represent a reduction in mortality and morbidity and the associated cost of such impacts. This methodology is critical to assessing the potential benefits of the current initiative to improve air quality implemented by the Environmental Metropolitan Commission of Mexico City.

## IMPLICATIONS

All of Mexico City's 17 million residents were exposed above the 24-hr maximum PM<sub>10</sub> standard, and almost all (96%) were exposed above the annual arithmetic average PM<sub>10</sub> standard. A 10% reduction scenario of the annual arithmetic average would represent a reduction in exposure to this standard of 1.9 million residents. The 20% reduction scenario would represent a reduction in exposure to this standard for up to 9.4 million people. Since human exposure to airborne PM is associated with mortality and morbidity impacts, achieving this latter scenario would represent a significant health benefit for the population of this metropolitan area.

## INTRODUCTION

The World Health Organization (WHO) and United Nations Environmental Program developed a joint report describing urban air pollution in megacities.<sup>1</sup> In this report, Mexico City ranked highest, with four out of the six pollutants considered exceeding, by a factor of 2, the WHO guidelines. This included total suspended particulate matter (PM), ozone, carbon monoxide, and sulfur dioxide. Nevertheless, in a more recent publication regarding Latin American megacities, it was observed that its air quality improved for the period of 1988–1997.<sup>2</sup>

The overall improvement has been accomplished through a series of efforts implemented by the local and federal governments in the region. The latest efforts to reduce emissions are being developed by the Metropolitan Environmental Commission (CAM) under the Third Air Quality Program 2000–2010. This program aims to ensure that, by 2010, air quality will substantially improve in terms of reduced ozone, volatile organic compounds,  $\text{NO}_x$ , and  $\text{PM}_{10}$ . This current study was developed to facilitate the valuation of the health and economic benefits of improving air quality under diverse scenarios for 2010.

### Background

One of the factors that makes it difficult to comply with the national and WHO air quality standards in Mexico City is its geographic location. The metropolitan area of Mexico City is situated in a valley surrounded by mountains at an average altitude of 2240 m above sea level, and at a latitude of 19.5° N. To the west and south are high mountains, with an average altitude higher than 3000 m, that cap the valley.<sup>3</sup> At this altitude and latitude, it receives high-energy solar radiation throughout the year. The climatic conditions favor an absence of winds and stationary masses of cold air in the winter, as well as thermal inversions aggravated by the surrounding mountains. The dry lake of Texcoco, to the east of Mexico City, has an incipient vegetation cover and is an important source of windblown dust. The area of the region is 7860 km<sup>2</sup>. In addition to the geographic conditions, Mexico City is a very densely populated area, with a recorded population of 16.6 million in 1995. It has a vehicle fleet of 2.7 million vehicles, and 80% of its inhabitants rely on public transportation. Total  $\text{PM}_{10}$  emissions are estimated at 32,000 tons/year.<sup>4</sup>

### Previous Studies

A number of studies have presented  $\text{PM}_{10}$  data for the Mexico City metropolitan area in the past decades. Data collected from 1988 and 1989 by the federal government reported daily maxima of up to 607  $\mu\text{g}/\text{m}^3$  and annual arithmetic averages ranging from 78 to 235  $\mu\text{g}/\text{m}^3$ .<sup>5</sup> More recently, a daily maximum of 542  $\mu\text{g}/\text{m}^3$  was reported in samplings conducted during March and April of 1997. Monthly averages for the period ranged from 39 to 108  $\mu\text{g}/\text{m}^3$ .<sup>6</sup> In both reports, there were trends of increasing fine PM from the southwest to the northeast and east of the metropolitan area. In independent studies, for the summer periods between July and August for the years 1987 to 1990, the average  $\text{PM}_{15}$  concentration was reported at 133  $\mu\text{g}/\text{m}^3$ .<sup>7</sup> Subsequent studies on  $\text{PM}_{15}$  reported average values of 106  $\mu\text{g}/\text{m}^3$  for the fall of 1993 at daytime in a southwestern site.<sup>8</sup> Using an independent station, for

the period between 1993 and 1995, Castillejos et al.<sup>9</sup> reported an average of 45  $\mu\text{g}/\text{m}^3$  for the southwestern part of Mexico City. This area has consistently been the low  $\text{PM}_{10}$  concentration area, according to Cicero et al.<sup>5</sup> and Edgerton et al.<sup>6</sup> Characterizations of the chemical composition of the particulate also have been presented, including elemental ions<sup>6–8,10</sup> and organic carbon.<sup>6,10</sup> The studies pointed out a significant contribution of crustal material<sup>8</sup> specifically from the eastern end of the metropolitan area.<sup>6</sup> Combustion or fuel sources represented a significant fraction of the  $\text{PM}_{2.5}$  fraction. Vega et al.<sup>10</sup> reported significant contributions from precatalyst gasoline vehicles in the  $\text{PM}_{2.5}$  from samples collected during 1989 and 1990. Edgerton et al.<sup>6</sup> also found important carbon-containing aerosols, and Miranda et al.<sup>8</sup> reported significant contributions from fuel oil and traffic.

### Association with Health Effects in Mexico City

In addition to reports of  $\text{PM}_{10}$  concentrations, a number of studies have linked health effects to air pollutants in residents of Mexico City. Air pollution has been associated with respiratory function and symptoms of susceptible populations, such as children, for example,<sup>11</sup> and explicitly with fine PM ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ).<sup>12</sup> Asthmatic children are very susceptible to air pollution, and associations have been reported for the case of Mexico City.<sup>13,14</sup> An increase of 20  $\mu\text{g}/\text{m}^3$  of  $\text{PM}_{10}$  was associated with an 8% increase in lower respiratory illness in asthmatic children.<sup>14</sup> Total suspended particles have been associated with total mortality in this metropolitan area,<sup>15,16</sup> as has  $\text{PM}_{2.5}$ .<sup>17</sup> In a more recent study, increases in mortality were associated with increases in  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , and the coarse fraction,  $\text{PM}_{10-2.5}$ . A 10- $\mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{10}$  was associated with a 1.48% increase in total mortality. The strongest effect was observed for  $\text{PM}_{10-2.5}$  with an increase of 10  $\mu\text{g}/\text{m}^3$  associated with a mean daily mortality increase of 4.07%.<sup>9</sup> Infant mortality, for children less than 1 year of age, has also been linked to fine particles in Mexico City. An increase in a 3-day mean of 10  $\mu\text{g}/\text{m}^3$  of  $\text{PM}_{2.5}$  was associated with a 6.9% increase in infant deaths.<sup>18</sup>

### Current $\text{PM}_{10}$ Mexican Standard

The Mexican Health Ministry adopted  $\text{PM}_{10}$  standards similar to those of the United States during 1994, that is, a 24-hr average of 150  $\mu\text{g}/\text{m}^3$  and an annual arithmetic average of 50  $\mu\text{g}/\text{m}^3$ .<sup>19</sup> It is clear that reducing the levels of fine PM would provide health benefits to the population of this large metropolitan area.

### METHODOLOGY

Exposure is commonly defined as contact between an agent and an organism,<sup>20</sup> in our case,  $\text{PM}_{10}$  and the human population of Mexico City. The temporally integrated

exposure is calculated in the discrete form as the summation of the products of individual concentrations encountered by an individual in a microenvironment and the time of exposure to each concentration in each microenvironment.<sup>21</sup> Currently, a wide range of exposure methods are in use, including the use of photochemical modeling and ambient data,<sup>22</sup> probabilistic modeling,<sup>23</sup> and a combination of approaches.<sup>24</sup> For the purpose of this study, we assume the exposure to PM<sub>10</sub> of ambient origin is equal to the air quality measured outdoors. This is an extreme assumption because most of the residents are not outdoors, all day, for a year. In addition, we assume no mobility of the population. This methodology required two basic inputs: spatial distributions of population, and air quality data based on air pollution measurement stations. The population-weighted exposure to a relevant air quality value in a municipality or delegation was defined as

$$AQM_{pwm} = \Sigma(AQM_{l,m} \times P_{l,m}) / \Sigma P_{l,m} \quad (1)$$

where  $AQM_{pwm}$  is the population-weighted air quality value in municipality/delegation  $m$ ;  $AQM_{l,m}$  is the air quality value in locality  $l$  in municipality/delegation  $m$ ; and  $P_{l,m}$  is the population in locality  $l$  in municipality/delegation  $m$ .

### Pollution Control Scenarios and Air Quality

A baseline scenario was developed taking into consideration the last 5 years of data. This will be described in detail in the following section. Additionally, three scenarios were developed. The first assumed a 10% decrease in concentrations from 2000 to 2010. A more aggressive scenario assumed a 20% decrease in concentrations in this period. Finally, an air quality standard compliance scenario was developed, where all the area is in conformity. At the time of developing the scenarios, no photochemical or particulate phase modeling was available.

### Geographical Information Systems

In conducting exposure assessments, it is necessary to characterize the distributions of pollutants spatially. In Mexico, the spatial representations of pollutant distributions have in the past been made using traditional cartographic tools.<sup>25</sup> More recently, air pollutant contours of the same concentration have been developed electronically, through interpolation software.<sup>5</sup> Now, the use of geographical information systems (GIS) permits linking different information attributes to a common geographical position for their subsequent classification, charting, and study. In this study, ArcView3.1 was used for this purpose.

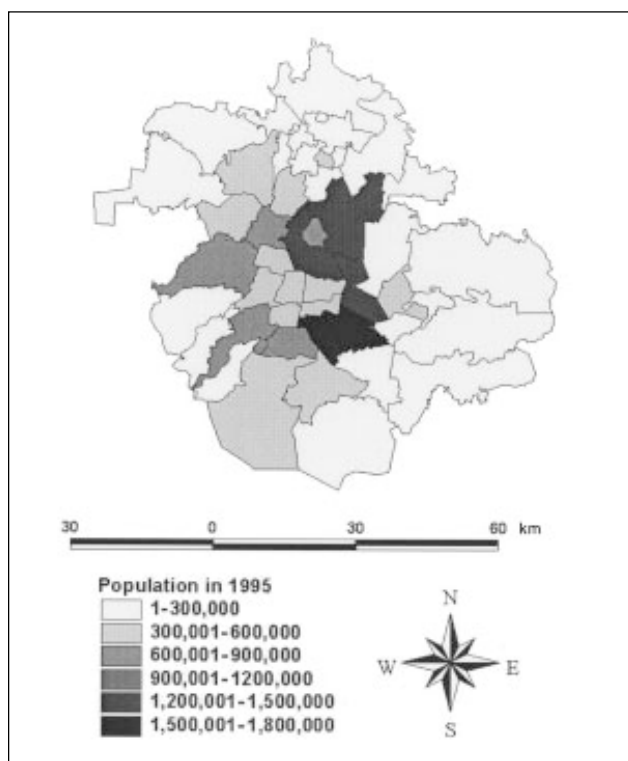
### Data Sources—Population

The Mexico City metropolitan area, with about 16.6 million people in 1995, is composed of the Federal District

(containing Mexico City and its 8.5 million people) and part of the State of Mexico. The projected population for the year 2010 is 19.5 million. Demographic information was obtained from the Mexican National Institute of Statistics, Geography and Information. The population was presented by localities (towns) in rural or semirural areas. Each locality was assigned to a municipality (in the State of Mexico) or to a delegation (in the Federal District). In more urbanized areas, the population was assigned directly to a municipality or delegation. The GIS work group at the Federal District Government provided a municipality and delegation boundary map. Figure 1 presents the population distribution for 1995.

### Data Sources—Air Quality

The Air Quality Monitoring Network of the Mexico City metropolitan area provided air quality data. The network includes ten PM<sub>10</sub> stations. Sample collection and data validation in these stations adhered closely to the U.S. Environmental Protection Agency procedures described in the Code of Federal Regulations<sup>26</sup> of the United States. In particular, the tapered element oscillating microbalance was designated as an equivalent method to measure PM<sub>10</sub> by the U.S. Federal Register<sup>27</sup> and operates with a heated inlet at 50 °C. The PM<sub>10</sub> monitoring sites were geocoded for use in the GIS. Table 1 presents a brief description of the air quality stations.



**Figure 1.** Metropolitan area of Mexico City population distribution for 1995.

**Table 1.** Mexico City metropolitan area PM<sub>10</sub> air quality monitoring stations.

Code	Name	Location	Description
LVI	La Villa	NE	Commercial and high-density residential site
TLA	Tlanepantla	NW	Industrial and medium-density residential site
XAL	Xalostoc	NE	Industrial and medium-density residential site
MER	Merced	Downtown	Commercial and high-density residential site
PED	Pedregal	SW	Low-density residential site
CES	Cerro Estrella	SE	Commercial and medium-density residential site
NET	Netzahualcoyotl	E	High-density residential site
TLI	Tultitlan	N	Suburban medium-density residential site
VIF	Coacalco	N	Suburban medium-density residential site
TAH	Tlahuac	SE	Suburban medium-density residential site

### Air Quality Data Management and Processing by Station

To develop the spatial distributions of air quality data in the metropolitan area of Mexico City, a baseline was developed to include the last 5 years of data. The period included data from 1995 to 1999. From these 5 years, a 1-year baseline distribution was developed for each measurement station data. The criteria to develop the “typical” 1-year distribution included the following requirements:

- (1) preservation of the average of the 5-year interval;
- (2) preservation of the standard deviation of the 5-year interval; and
- (3) preservation of the maximum concentration within the 5-year interval.

For the first two requirements, random sampling of the 5-year interval would have led to a reasonable 1-year distribution with a similar standard deviation. But in a random sample, no guarantee of preserving the maximum would be possible. Instead, a targeted sampling strategy was utilized to preserve, as close as possible, the original distribution. The 5 years of data were sorted from highest to lowest and sampled proportionally starting with the maximum to obtain 365 evenly distributed data points per station. The distribution of the PM<sub>10</sub> daily 24-hr average was developed. The development of a 1-year distribution simplified the comparisons with future scenarios, specifically for environmental alert estimations. In Table 2, the relevant statistics for the original 5-year data set

compared to the baseline data set is given, including number of valid data, mean, standard deviation, and minimum and maximum.

### Control Scenario Impact on Environmental Alerts

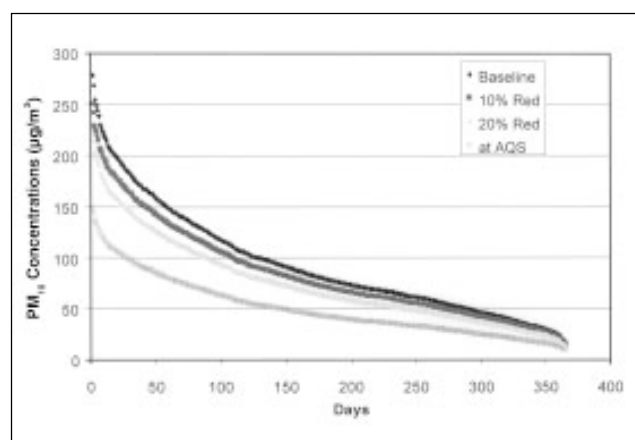
Baseline distributions were developed for environmental alerts in the Mexico City metropolitan area to analyze the impact of the proposed control scenarios. Environmental alerts are linked to the maximum concentration in the metropolitan area. Thus, for each day, the maximum PM<sub>10</sub> concentration of all the stations was selected. Then, the proportional sampling was performed to obtain 365 data points for the baseline. Next, distributions for each control scenario were developed (achieving a 10% reduction in concentrations, a subsequent one of 20% reductions, and a final distribution for the achievement of the air quality standards throughout the city). These scenarios were developed for the 24-hr average for PM<sub>10</sub>. Figure 2 presents the baseline distributions and the three scenarios.

### Spatial Air Quality and Population Data Management and Processing

Once the 1-year baseline distributions were generated by station, the maximum and the annual average were estimated for the PM<sub>10</sub> daily 24-hr average. Each station was geocoded and linked to the spatial domain of the metropolitan area of Mexico City. It was assumed that the air quality at the border of the spatial domain modeled would be equal to the lowest concentration observed within this domain. This supposition assumes that influence of transport of air pollutants is minimal, but it has not been tested observationally. A spatial distribution was developed using the inverse distance weighting method using six neighbors and power of 2. This minimized distortions and spurious interpolations and extrapolations. This method

**Table 2.** PM<sub>10</sub> statistics for the original 5-year data and baseline 1-year data (24-hr average).

Station	N	Original 5-Year Data Set				N	Baseline 1-Year Data Set			
		Mean	Std	Min	Max		Mean	Std	Min	Max
LVI	1802	55	27	11	214	365	56	27	13	214
TLA	1749	63	36	9	275	365	63	37	11	275
XAL	1650	94	53	13	278	365	94	53	17	278
MER	1770	68	39	9	319	365	69	41	11	319
PED	1765	49	28	8	264	365	49	29	9	264
CES	1732	65	35	11	268	365	65	36	13	268
NET	1540	89	45	11	335	365	89	46	16	335
TLI	1111	54	28	10	190	365	54	28	11	190
VIF	1099	49	27	9	201	365	50	27	9	201
TAH	1186	52	32	10	238	365	52	33	10	238



**Figure 2.** Baseline distributions for  $PM_{10}$  and the three scenarios (10% reduction, 20% reduction, and achieving the 24-hr maximum air quality standard at Station Xalostoc).

has been evaluated as a feasible method to interpolate long-term ozone concentrations.<sup>28</sup> The Federal District comprises 16 delegations and the State of Mexico comprises 28 municipalities within the metropolitan area. Within each municipality or delegation, population localities were identified. To each of these localities, the corresponding air quality value was associated.

## RESULTS AND DISCUSSION

The baseline concentrations were analyzed per station for the two  $PM_{10}$  standards, daily average ( $150 \mu\text{g}/\text{m}^3$ ) and annual average ( $50 \mu\text{g}/\text{m}^3$ ). At all stations, except at Station Pedregal and Coacalco, both standards were violated. The highest concentrations were observed in the eastern part of the metropolitan area, with a daily maximum observed at Station Netzahualcoyotl at  $335 \mu\text{g}/\text{m}^3$ . The highest annual average was observed at Station Xalostoc at  $94 \mu\text{g}/\text{m}^3$  (see Table 2). These findings are consistent with previous studies.<sup>6</sup> It is apparent that the annual average concentrations have been decreasing; however, the maximum concentration did not have an overall decreasing trend<sup>5</sup> when compared with data collected during 1988–1989. The daily average air quality standard is exceeded 87 days per year (24% of the year) in at least one station. The baseline population weighted maximum concentration for the metropolitan area was a  $261\text{-}\mu\text{g}/\text{m}^3$  daily average and a  $64\text{-}\mu\text{g}/\text{m}^3$  annual average. Table 3 summarizes this information as well as the projected population. The estimated reductions in the population-weighted  $PM_{10}$  annual average exposure are 6.4, 12.8, and  $14.0 \mu\text{g}/\text{m}^3$  for the 10%, 20%, and complying with the air quality standard reduction scenarios, respectively, for the typical inhabitant. Spatially, the higher  $PM_{10}$  annual average concentrations were observed at the northeastern border between the federal district and the State of Mexico as

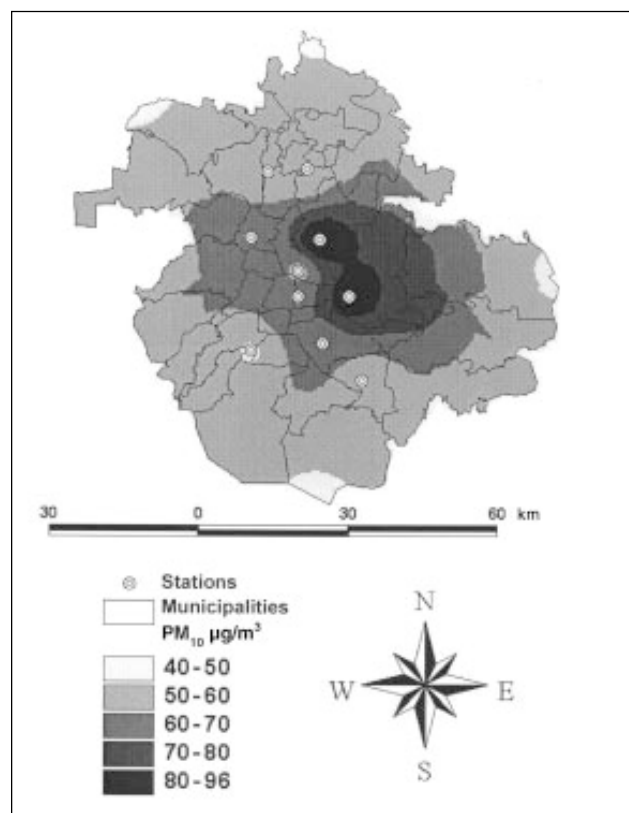
**Table 3.** Summary of air quality metrics and population by entity and the metropolitan area of Mexico City.

Air Quality Metrics		Federal District	State of Mexico	Metropolitan Area
$PM_{10}$ ( $\mu\text{g}/\text{m}^3$ )	Daily maximum	248	228	236
	Daily maximum, population-weighted	268	254	261
24-hr	Annual average	56	58	57
	Annual average, population-weighted	62	65	64
Total population (millions)	1995	8.49	8.14	16.63
	2000	8.57	9.12	17.69
	2010	8.67	10.80	19.47

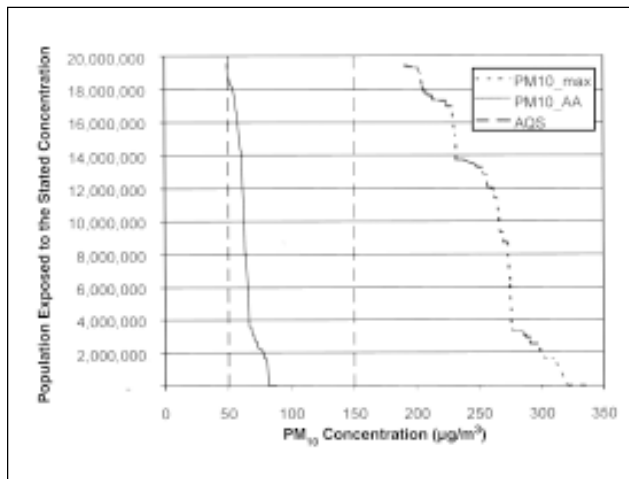
presented in Figure 3. This area contains the largest population in the metropolitan area (see Figure 1). The municipality of Netzahualcoyotl, located at that border, had the highest population-weighted daily maximum and annual average with values of  $310$  and  $81 \mu\text{g}/\text{m}^3$ , respectively (see also station NET in Table 2).

## Population Exposure

Figure 4 presents the population exposed to baseline daily maximum and annual average concentrations



**Figure 3.** Baseline spatial distribution for the  $PM_{10}$  annual average concentrations in the metropolitan area of Mexico City.



**Figure 4.** Baseline distribution of population exposed to 24-hr maximum concentrations and annual arithmetic average concentrations of  $PM_{10}$  for 2010 in the metropolitan area of Mexico City (lines at 50 and 150  $\mu\text{g}/\text{m}^3$  denote the air quality standards).

projected for 2010. Table 4 presents the estimations for the population, per age group, exposed at the relevant  $PM_{10}$  level. The baseline is presented for 1995 and 2010, and the control scenarios only for estimations for 2010. All the population will be exposed at least once to levels above the daily average air quality standard if the emissions in the region remain the same. The reduction scenarios of 10 and 20% did not affect the number

of people exposed to exceedences of the daily air quality standard. In a similar way, most of the population (96%) will be exposed to exceedences of the annual average air quality standard. In contrast to the daily maximum, the 10% reduction scenario will decrease by 1.9 million people exposed to violations of the annual standard, and the 20% reduction scenario will provide a decrease of exposure to violations of 9.4 million people in 2010. When considering the Stage I environmental alert level of 300  $\mu\text{g}/\text{m}^3$ , for the baseline, about 1.6 million people will be exposed at least once to this concentration. In this case, the 10% reduction scenario will eliminate this exposure.

### By Age Group

The study estimated that for the baseline scenario, about a half million infants of less than a year, 2.3 million preschool children (1–5 years), 2.6 million school children (6–11 years), 1.3 million junior high students (12–14 years), and slightly more than a half million seniors (65 years or more) will be exposed above the annual air quality standard if emissions continue at the current level (see Table 4). For the same baseline at extreme Stage I episode levels higher than 300  $\mu\text{g}/\text{m}^3$ , exposures would be as follows: 40,000 infants, 200,000 preschool children, 230,000 school children, 110,000 junior high students, and 50,000 seniors.

**Table 4.** Summary of population exposed by age groups to relevant  $PM_{10}$  levels and scenario estimates. The baseline is presented for 1995 and 2010. For the control scenarios, only estimations for 2010 are presented.

			General Population (in %) (millions)		Less than a Year (millions)	1 to 5 Years (millions)	6 to 11 Years (millions)	12 to 14 Years (millions)	15 to 64 Years (millions)	65 Years and More (millions)
Daily Maximum		µg/m³								
1995	Baseline	>300	1.24	(7%)	0.03	0.15	0.17	0.09	0.76	0.04
		>270	7.84	(47%)	0.20	0.95	1.09	0.54	4.81	0.25
		>150	16.63	(100%)	0.42	2.03	2.30	1.15	10.21	0.52
2010	Baseline	>300	1.63	(8%)	0.04	0.20	0.23	0.11	1.00	0.05
		>270	8.80	(45%)	0.22	1.07	1.22	0.61	5.40	0.28
		>150	19.46	(100%)	0.49	2.37	2.70	1.34	11.95	0.61
	10% Reduction	>300	0	(0%)	0	0	0	0	0	0
		>270	1.63	(8%)	0.04	0.20	0.23	0.11	1.00	0.05
		>150	19.46	(100%)	0.49	2.37	2.70	1.34	11.95	0.61
	20% Reduction	>300	0	(0%)	0	0	0	0	0	0
		>270	0	(0%)	0	0	0	0	0	0
		>150	19.46	(100%)	0.49	2.37	2.70	1.34	11.95	0.61
Annual Average		µg/m³								
1995	Baseline	>50	15.90	(96%)	0.40	1.94	2.20	1.10	9.76	0.50
2010	Baseline	>50	18.72	(96%)	0.47	2.28	2.60	1.29	11.49	0.59
	10% Reduction	>50	16.82	(86%)	0.42	2.05	2.33	1.16	10.33	0.53
	20% Reduction	>50	9.35	(48%)	0.24	1.14	1.30	0.64	5.74	0.29

Note: Data were rounded to the nearest 10,000 inhabitants.



**Table 5.** Number of days that relevant PM<sub>10</sub> levels are exceeded and scenario estimates.

µg/m <sup>3</sup>	Baseline	10% Reduction	20% Reduction	At Standard
>300	1	0	0	0
>270	2	1	0	0
>150	87	42	26	0

### Environmental Alerts

In the metropolitan area of Mexico City, the main concerns of air pollution are the impact on human health and also the restrictions put on economic activity when excessive levels are reached. When a Stage I environmental alert is declared, it restricts economic activity by limiting the activities of a range of manufacturing industries that generate emissions of air pollutants, and also by restricting traffic. For PM<sub>10</sub>, only one Stage I environmental alert per year was estimated for the baseline. The 10% reduction scenario prevents the occurrence of such high levels. Table 5 presents the exceedences of the pre-alert level of 270 µg/m<sup>3</sup> and the 300 µg/m<sup>3</sup> Stage I level, as well as the estimations for the control scenarios.

### CONCLUSIONS

The study highlights the severity of the air pollution levels in the metropolitan area of Mexico City, despite the improvements in the air quality when compared with earlier studies.<sup>2,5</sup> The improvements in air quality over a decade are evident for the annual averages, but for the daily maxima improvement they are less evident. The implementation of actions to reduce the levels of air pollution may achieve important health benefits, as well as preventing economic losses by the implementation of environmental alert measures. The improvements of air quality may benefit sensitive populations that have been linked to adverse effects of airborne PM. Such is the case with school children and, specifically, those with childhood asthma. In addition, excess mortality may be prevented by future control measurements in the general population and in sensitive groups. In this analysis, it was found that up to 30,000 infants and 40,000 seniors were exposed to very high levels of PM<sub>10</sub> during 1995, and if no measures are taken for 2010, the number may rise to 40,000 and 50,000, respectively. The results address only concentrations of PM, but the adverse effects may be compounded if other pollutants, such as ozone, are included.

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